# MPI in PYTHIA 8

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# Overview

# MPI in PYTHIA 8

## Interleaved evolution

- Note: what follows covers the current MPI framework of PYTHIA 8

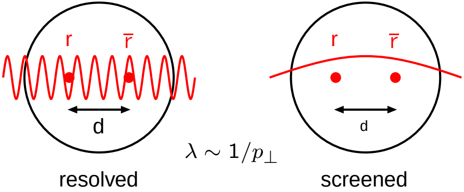
- Transverse-momentum-ordered parton showers
- MPI also ordered in $p_\perp$
  - Mix of possible underlying event processes, including jets, $\gamma$, $\mathrm{J}/\psi$, DY, ...
  - Radiation from all interactions
- Interleaved evolution for ISR, FSR and MPI

$$
\begin{aligned}
\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} &= \left( \frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right) \\
&\times \exp \left( - \int_{p_\perp}^{p_{\perp\max}} \left( \frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)
\end{aligned}
$$

- Ordered in decreasing $p_\perp$ using "Sudakov" trick

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \exp\left( - \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp \right)$$

- QCD $2 \to 2$ cross section divergent in $p_\perp \to 0$ limit, but q/g not asymptotic states




- Regularise cross section, $p_{\perp 0}$ is now a free parameter

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

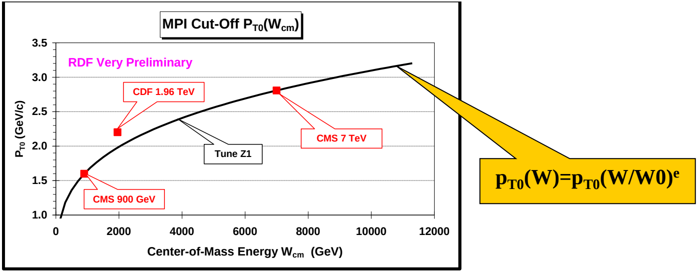
# MPI in PYTHIA 8

## $p_{\perp 0}$ and energy scaling

- $p_{\perp 0}$ depends on energy
- Ansatz: scales in a similar manner to the total cross section (effective power related to the Pomeron intercept)

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left( \frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}} \right)^{E_{\mathrm{CM}}^{\mathrm{pow}}}$$

- Need many measurements at different energies
  - Rick Field, MB & UE Working Group, Tune Z1 (PYTHIA 6)



# MPI in PYTHIA 8

## Impact parameter

- Require one interaction for a physical event
- Introduce impact parameter, $b$, with matter profile
  - Single Gaussian; no free parameters
  - Overlap function

$$\exp\left(-b^{E_{\mathrm{exp}}^{\mathrm{pow}}}\right)$$

  - Double Gaussian

$$\rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^3} \exp\left(-\frac{r^2}{a_2^2}\right)$$

- Time-integrated overlap of hadrons during collision
  - Average activity at $b \propto \mathcal{O}(b)$

$$\mathcal{O}(b) = \int \mathrm{d}t \int \mathrm{d}^3 x \rho(x,y,z)\, \rho(x+b,y,z+t)$$

  - Central collisions usually more active
  - Probability distribution broader than Poissonian

- ISR and MPI compete for beam momentum $\rightarrow$ PDF rescaling
- Squeeze original $x$ range

$$0 < x < 1 \quad \rightarrow \quad 0 < x < \left(1 - \sum x_i\right)$$

- Flavour effects
  - Sea quark initiator $(\mathrm{q}_s)$ leaves behind an anti-sea companion $(\mathrm{q}_c)$
  - $\mathrm{q}_c$ distribution from $\mathrm{g} \rightarrow \mathrm{q}_s + \mathrm{q}_c$ perturbative ansatz
  - Normalisation of sea + gluon distributions fluctuate for total momentum conservation

- Primordial $k_\perp$
  - Needed for agreement with e.g. $p_\perp(\mathrm{Z}^0)$ distributions
  - Give all initiator partons Gaussian $k_\perp$, width

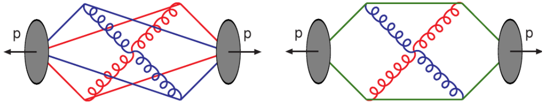
$$\sigma(Q, \widehat{m}) = \frac{Q_{\frac{1}{2}}\, \sigma_{\mathrm{soft}} + Q\, \sigma_{\mathrm{hard}}}{Q_{\frac{1}{2}} + Q} \; \frac{\widehat{m}}{\widehat{m}_{\frac{1}{2}} + \widehat{m}}$$

  - Rotate/boost systems to new frame

# MPI in PYTHIA 8

## Colour reconnection

- Rearrangement of final-state colour connections such that overall string length is reduced

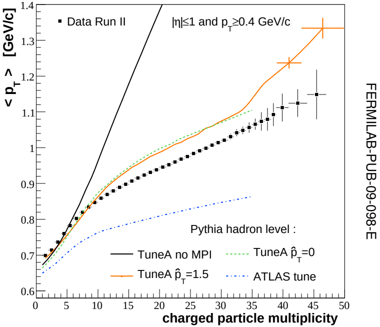



- Large amount of reconnection required for agreement with data

- Probability for a system to reconnect with a harder system

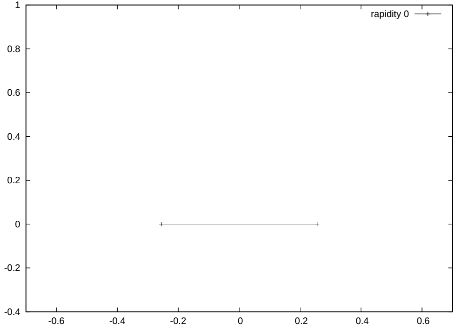
$$\mathcal{P} = \frac{p_{\perp R}^2}{(p_{\perp R}^2 + p_\perp^2)} ,$$

$$p_{\perp R} = R * p_{\perp 0}^{\mathrm{MI}}$$



# Enhanced screening

- Idea of Gösta Gustafson from work on modeling initial states with an extended Mueller dipole formalism
  - "Elastic and quasi-elastic *pp* and $\gamma^* p$ scattering in the Dipole Model," C. Flensburg, G. Gustafson and L. Lönnblad, Eur. Phys. J. C **60** (2009) 233




- Even at fixed impact parameter, initial state will contain more/less fluctuations on an event-by-event basis
  - More activity $\rightarrow$ more screening

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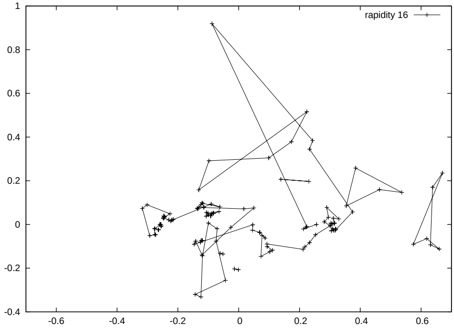


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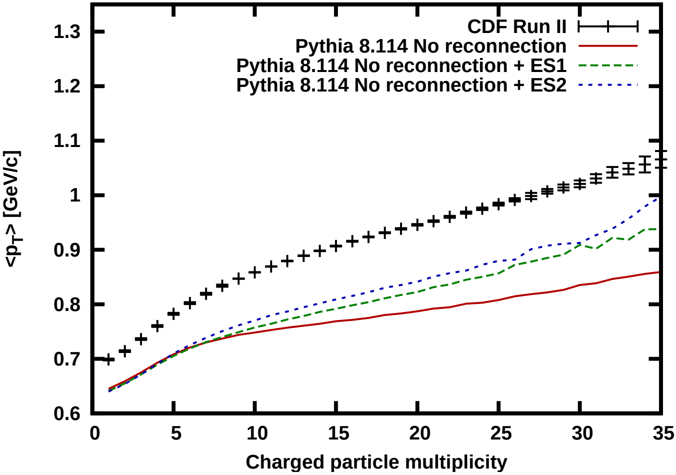
# Enhanced screening

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_S^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \rightarrow \frac{\alpha_S^2(p_{\perp 0}^2 + p_\perp^2)}{(n\,p_{\perp 0}^2 + p_\perp^2)^2}$$

ES1: $n$ = no. of MI
ES2: $n$ = no. of MI + ISR



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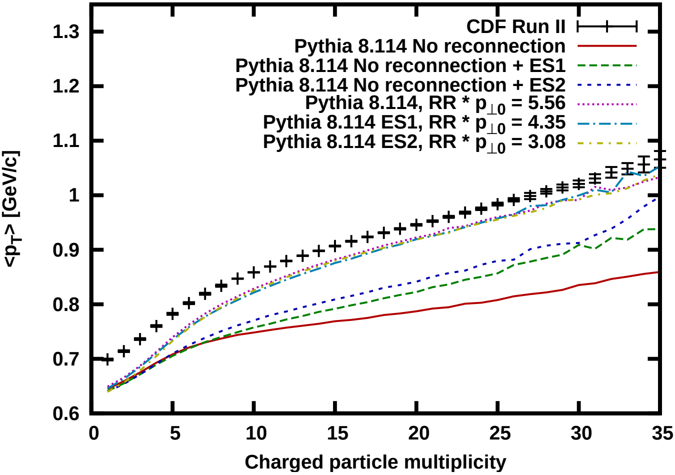
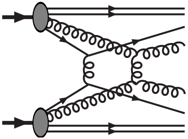
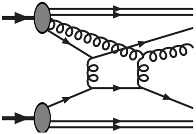


# Rescattering

- MPI traditionally disjoint $2 \to 2$ interactions
- Rescattering: allow an already scattered parton to interact again





- Investigated by Paver and Treleani (1984), size of effect

$$\frac{\mathrm{d}\sigma_{\mathrm{int}}}{\mathrm{d}p_\perp^2} = \sum \int \mathrm{d}x_1 \int \mathrm{d}x_2 \int f_1(x_1, Q^2)\, f_2(x_2, Q^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \sim N_1 N_2 \hat{\sigma}$$

$$\sigma_{4\to 4} \sim (N_1 N_2 \hat{\sigma})(N_1' N_2' \hat{\sigma}) \qquad \sigma_{3\to 3} \sim (N_1 N_2 \hat{\sigma})(N_1' \hat{\sigma})$$

$$\frac{\sigma_{3\to 3}}{\sigma_{4\to 4}} \sim \frac{1}{N_2'} \to \mathrm{small}$$

- But should be there!
  - Plays a role in the collective effects of MPI
  - Possible colour connection effects

# Rescattering

- Typical case of small angle scatterings between partons from 2 incoming hadrons, such that they are still associated with their original hadrons

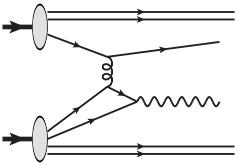
$$f(x, Q^2) \rightarrow f_{\mathrm{rescaled}}(x, Q^2) + \sum_n \delta(x - x_n)$$

- In this limit, momentum sum rule holds

$$\int_0^1 x\, f_{\mathrm{rescaled}}(x, Q^2)\, \mathrm{d}x + \sum_n x_n = 1$$

- Original MPI interactions supplemented by:
  - Single rescatterings: one parton from the rescaled PDF, one delta function
  - Double rescatterings: both partons are delta functions

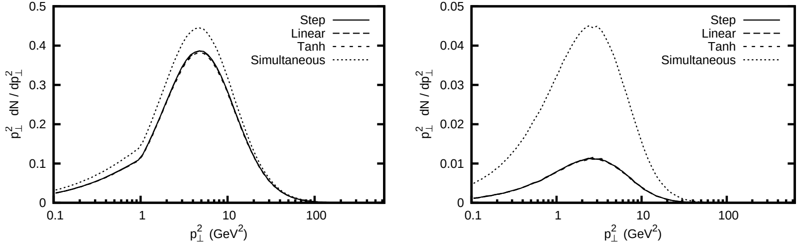
- One simplification: rescatterings always occur at "later times"
  - $\mathrm{Z}^0$ preceeded by rescattering not possible



# Rescattering

- In general not possible to uniquely identify a scattered parton with an incoming hadron, so use approximate rapidity based prescription

| | |
|---|---|
| Step: | Step function at $y = 0$ |
| Simultaneous: | Partons belong to both beams simultaneously |
| Tanh/linear: | In between |




- Little sensitivity to choice
  - Natural suppression for single rescattering
  - No suppression for double rescattering, but still small effect

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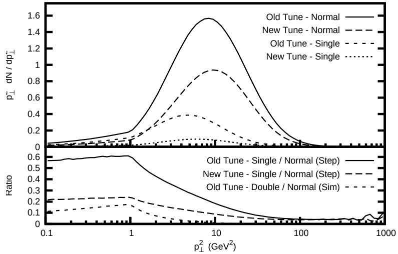


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# Rescattering

- Use step prescription
- Amount of rescattering sensitive to amount of underlying activity
  - Default tune change starting with PYTHIA 8.127
  - MPI: $p_{\perp 0}^{\text{ref}} = 2.15 \to 2.25$, $E_{\text{CM}}^{\text{pow}} = 0.16 \to 0.24$
  - Matter profile from double to single Gaussian
  - ISR activity increased

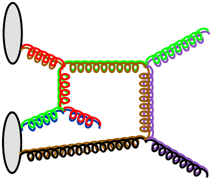
| | | Tevatron | | LHC | |
|---|---|---|---|---|---|
| | | Min Bias | QCD Jets | Min Bias | QCD Jets |
| Old | Scatterings | 2.81 | 5.09 | 5.19 | 12.19 |
| | Single rescatterings | 0.41 | 1.32 | 1.03 | 4.10 |
| | Double rescatterings | 0.01 | 0.04 | 0.03 | 0.15 |
| New | Scatterings | 2.50 | 3.79 | 3.40 | 5.68 |
| | Single rescatterings | 0.24 | 0.60 | 0.25 | 0.66 |
| | Double rescatterings | 0.00 | 0.01 | 0.00 | 0.01 |

Tevatron: $\text{p}\bar{\text{p}}$, $\sqrt{s} = 1.96$ TeV, QCD jet $\hat{p}_{\perp \text{min}} = 20$ GeV  LHC: pp, $\sqrt{s} = 14$ TeV, QCD jet $\hat{p}_{\perp \text{min}} = 50$ GeV

- Double rescattering always small, so ignored in what follows

# Rescattering

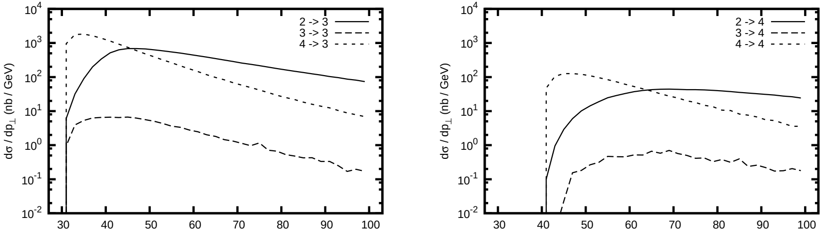
- So far nice and simple, but want fully hadronic events
  - Integration with showers needed
  - Keep system mass/rapidity unchanged where possible
- Colour effects
  - Parton showers use dipole picture for recoil
  - With rescattering, colour can flow between systems



- Full event generation, including showers, primordial $k_\perp$ and colour reconnections

# Rescattering

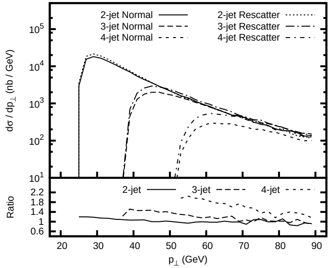
- Compare sources of 3- and 4-jets at the parton level
- Contributions to 3-jet rate
  - $2 \to 3$ from single radiation
  - $3 \to 3$ from single rescattering
  - $4 \to 3$ double parton scattering with one jet lost
- Contributions to 4-jet rate
  - $2 \to 4$ from double radiation
  - $3 \to 4$ from single radiation + single rescattering
  - $4 \to 4$ from DPS
  - $4 \to 4'$ from two single rescatterings




pp, $\sqrt{s} = 14$ TeV, new tune, $p_\perp > 10$ GeV, $|\eta| < 1.0$

# Rescattering

- Hadron level
  - Feed results into FastJet, anti-$k_\perp$ algorithm, $R = 0.4$
  - 2-, 3- and 4-jet exclusive cross sections
  - Some increase in jet rates, but contributions can be "compensated" by changes in parameters elsewhere




pp, $\sqrt{s} = 14$ TeV, old tune, $p_\perp > 12.5$ GeV, $|\eta| < 1.0$

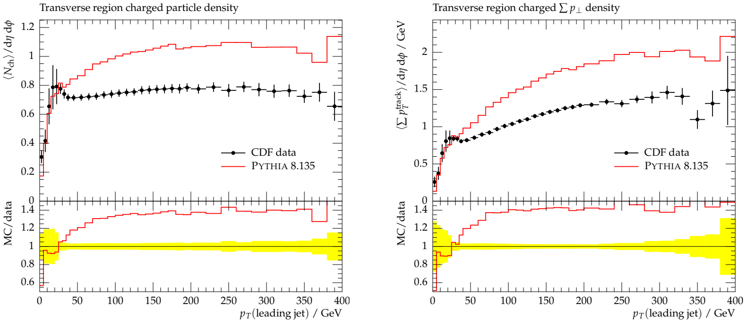
- Also studied
  - Colour reconnections
  - "Cronin" effect
  - $\Delta R$ & $\Delta\phi$ distributions
- No "smoking-gun" signatures for rescattering
- Would any effects be visible in a full tune?

# References

- PYTHIA references
  - "PYTHIA 6.4 Physics and Manual,"
    T. Sjöstrand, S. Mrenna and P. Z. Skands, JHEP **0605** (2006) 026
  - "A Brief Introduction to PYTHIA 8.1,"
    T. Sjöstrand, S. Mrenna and P. Z. Skands,
    Comput. Phys. Commun. **178** (2008) 852
- Model references
  - "A Multiple Interaction Model for the Event Structure in Hadron Collisions,"
    T. Sjöstrand and M. van Zijl, Phys. Rev. D **36** (1987) 2019
  - "Multiple interactions and the structure of beam remnants,"
    T. Sjöstrand and P. Z. Skands, JHEP **0403** (2004) 053
  - "Transverse-momentum-ordered showers and interleaved multiple interactions,"
    T. Sjöstrand and P. Z. Skands, Eur. Phys. J. C **39** (2005) 129
  - "Multiparton Interactions and Rescattering,"
    R. Corke and T. Sjöstrand, JHEP **1001** (2010) 035

# Tuning prospects

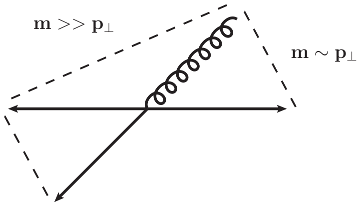
- FSR and hadronisation tuned to LEP data (H. Hoeth)
  - Already default for PYTHIA 8.125 and later
- Problems with simultaneous tuning of MB and UE



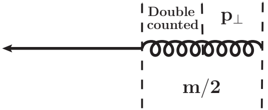

- MB well described, but UE rises too fast!

# Tuning prospects

- New in PYTHIA 8: FSR interleaving
  - Final-state dipoles can stretch to the initial state (FI dipole)
  - How to subdivide FSR and ISR in an FI dipole?
- Large mass $\rightarrow$ large rapidity range for emission



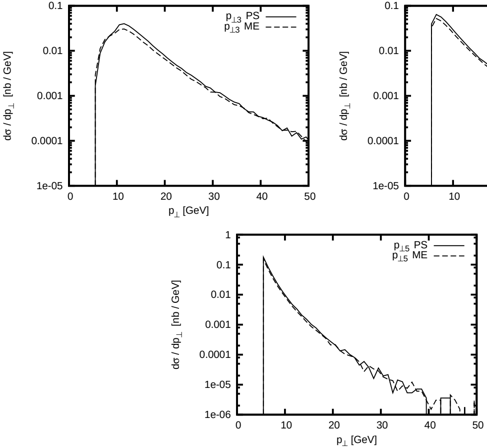

- In dipole rest frame




- Suppress final-state radiation in double-counted region

# Tuning prospects

- Also study how well the parton shower fills the phase space
  - Compare against $2 \to 3$ real matrix elements
  - Would changing the shower starting scale give better agreement?
  - Qualitatively, PS doing a good job



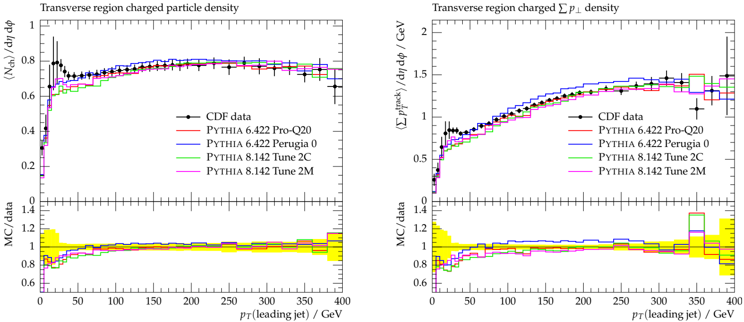

$p_{\perp 3}^{\min} = 5.0$ GeV

$p_{\perp 5}^{\min} = 5.0$ GeV

$R_{\mathrm{sep}} = 0.25$

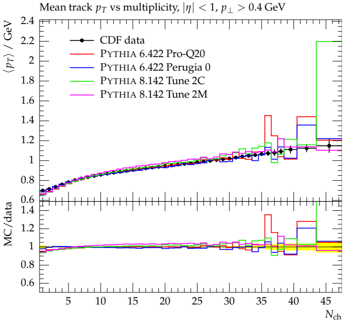
# Tuning prospects

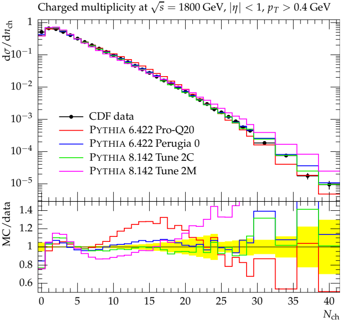
- Is a simultaneous MB/UE Tevatron tune now possible?
- Tunes 2C and 2M
  - CTEQ6L1 and MRST LO** PDF tunes to Tevatron data
  - Start with by-hand tune
- Compare against Pro-Q20 and Perugia 0
  - Underlying event description improved!



# Tuning prospects

- More plots: `http://www.thep.lu.se/~richard/pythia81`




- Broadly in line with previous tunes
- MRST LO** has more momentum
  - Lower $\alpha_s$ and higher $p_{\perp 0}^{\mathrm{ref}}$
- Use overlap function for matter profile
  - Parameter gives handle on width of multiplicity distributions
  - Suggests slightly wider than single Gaussian
- Reduced colour reconnection

# Tuning prospects

- New LHC data
  - Measurements of MB/UE at new energies!
  - Experiments appear consistent with themselves
  - But tension with older data?
- Move from NSD/INEL to INEL$>$0
  - Reproducible definitions!
- Diffractive description more important?
  - New framework in PYTHIA 8 for high-mass diffraction
  - "Diffraction in Pythia," S. Navin, arXiv:1005.3894 [hep-ph]
  - Based on Ingelman–Schlein picture
  - Single diffraction: Pomeron emitted from one incoming hadron interacts with incoming hadron on the other side
- Total cross sections
  - Early look at MB numbers suggest dampening diffractive cross sections?
  - New possibility to dampen rise available
  - ATLAS-CONF-2010-048: "Both PYTHIA8 and PHOJET would do slightly better in describing the data if there was an increase in the ND component"

# Summary

- PYTHIA 8 MPI model
  - Well established model that has evolved over time
  - Fully interleaved with parton showers
  - Rich mix of possible underlying event processes
- Still under development
- Enhanced screening
  - Perhaps part of a solution towards lowering colour reconnections
  - More evidence to come from DIPSY?
- Rescattering
  - First model to include such effects
  - No distinctive signatures; perhaps full tune would reveal more
- Future project: $x$-dependent proton profile
- Tuning prospects
  - Simultaneous MB/UE tuning within reach
  - Initial tunes to Tevatron data
  - Impact of LHC data still uncertain
  - Article in preparation